Lepton & Gamma Colliders for the Energy Frontier

Mark Palmer
Frontier Capabilities:
Energy Frontier Lepton & Gamma Colliders Sub-Group

CSS2013, June 28-August 6: “Snowmass on the Mississippi”

Fermilab

Outline

- Introduction
- Circular e^+e^-
- ILC
- Other LC Concepts
- $\gamma-\gamma$ Colliders
- μ Collider
- Closing Comments

The Working Group and Inputs

The Working Group Assessments

Comments on Making Comparisons

INTRODUCTION

Frontier Capabilities: Lepton Colliders

- Accelerator Capabilities Convener: Bill Barletta (MIT)

- Lepton Colliders Working Group:
  - Sub-conveners: Marco Battaglia (UCSC), Markus Klute (MIT), Kaoru Yokoya (KEK), & myself
  - EF Liaison: Tor Raubenheimer (SLAC)
  - Sub-Group Meeting at MIT: https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=233944

- Submissions covered a broad range of capabilities and possibilities ⇨ many contributors to what follows

Working Group Assessment

- The goal of the working group has been to:
  - Summarize the capabilities that can support the physics needs of Energy Frontier
  - Evaluate the major technical challenges and cost drivers
  - Identify the R&D path required to develop the necessary capabilities

- It should be noted that:
  - All of the options have some technical challenges
  - None of the options under consideration is cheap
  - But, we do have real options with contrasting strengths and weaknesses (as well as varying states of readiness) ⇨ which makes the process of charting an optimal route forward challenging when we are discussing timescales of decades

Comment on Concept Maturity

- It should also be noted that the concepts described here span a broad range of maturity
  - R&D concepts requiring significant validation
  - Full technical designs where performance has been explicitly sacrificed in order to achieve something that can be built
    - And to fit within a specific budget profile
  - Design extrapolations
    - Based on well-understood individual technologies in many cases
    - However, not yet validated in full detail

- Thus capabilities comparisons are non-trivial at this level
  - Attention should be paid to “strategic” (ie, physics) benefits
  - Audience should ask pointed questions about how realistic any individual plan is

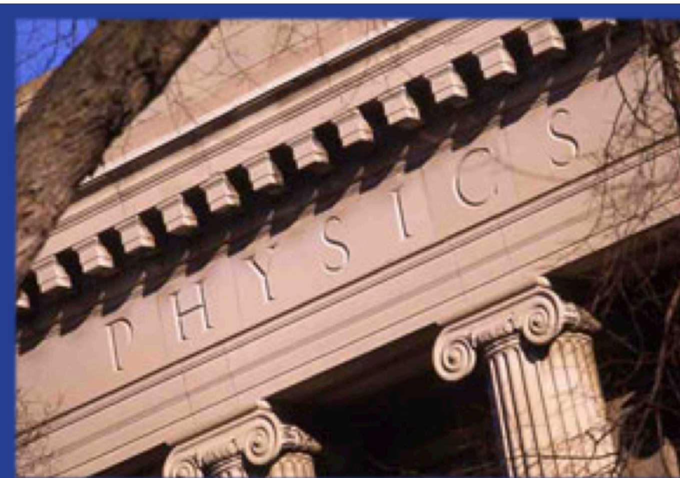
e^+e^- Circular Colliders:

>100 GeV Scale

Linear Colliders:

- e^+e^- Colliders with
  E < 1 TeV & E1> 1 TeV
- γ-γ Colliders

$\mu^+\mu^-$ Colliders: Up to 10 TeV



LEPTON & PHOTON COLLIDERS

e^+e^- Circular Colliders

Comments

- LEP2 nearly reached the Higgs
- Rings are robust and well-understood technology

Technical Issues

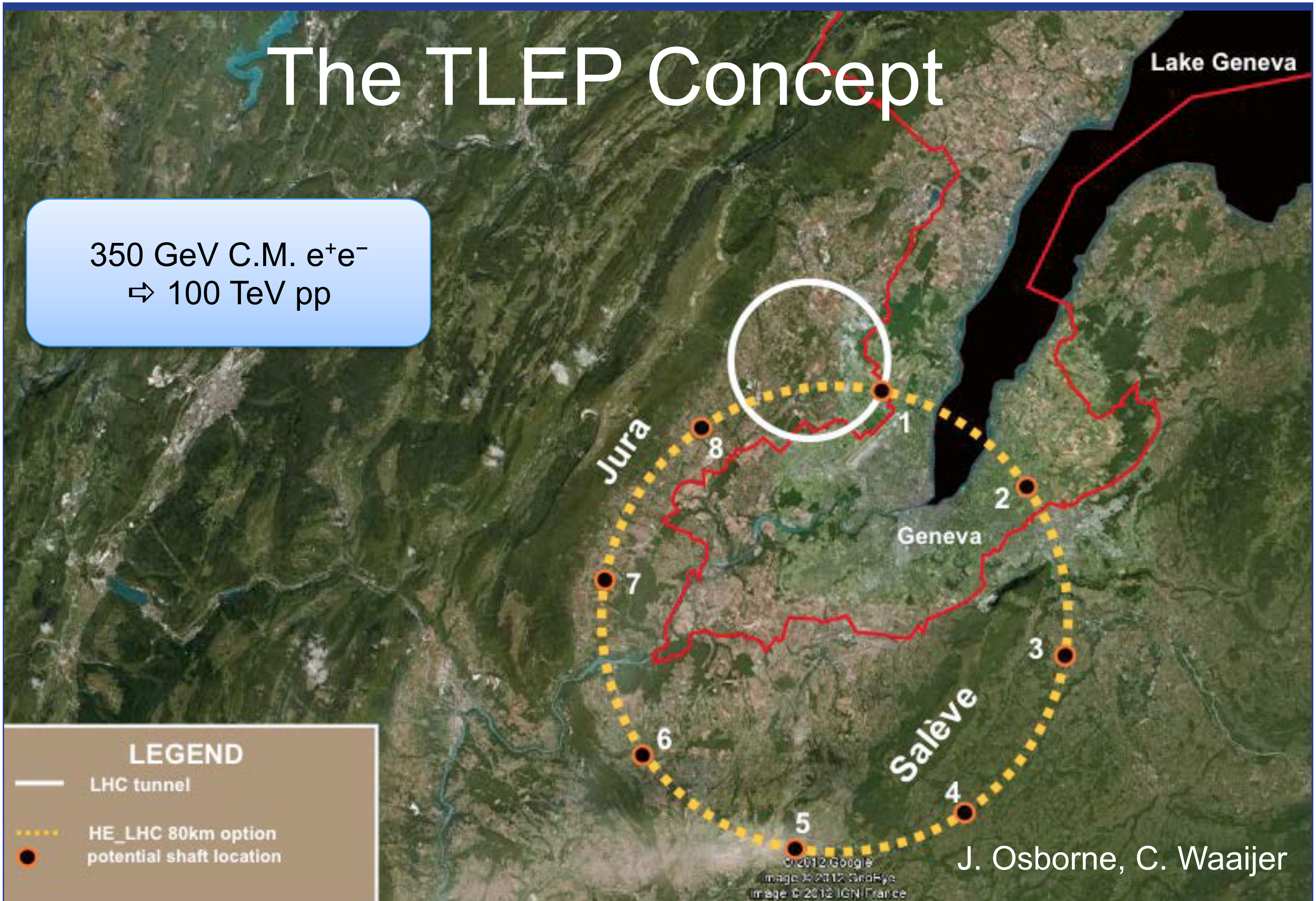
- Synchrotron Radiation: $\Delta E[GeV] = 8.85 \times 10^{-5} \frac{E^4[GeV^4]}{\rho[m]}$
- RF Efficiency
- Beam Lifetime (~10^3 sec) and Top-Up Injection
- Collective Effects
- Energy Bandwidth

Trends in the Discussion

- Re-use of the LEP tunnel (conflict w/LHC) as well as various site-filler options initially discussed
- Recent focus: 80-100km ring leading to a 100 TeV scale hadron collider (VHE-LHC/VLHC)
  - Takes a longer term view
  - Limits SR issues

The TLEP Concept

350 GeV C.M. e^+e^-
⇨ 100 TeV pp



J. Osborne, C. Waaijer

Electron-Positron Storage Rings: Parameters for Selected Options

	LEP2	TLEP* – HZ	TLEP* - t	FNAL** - HZ
Beam Energy [GeV]	104.5	120	175	120
Circumference [km]	26.7	80	80	100
Beam current [mA]	4	24.3	5.4	12.9
Number of bunches	4	80	12	34
Bunch population [10^{12}]	0.575	40.8	9.0	0.79
Horizontal emittance [nm]	48	9.4	10	16
Vertical emittance [nm]	0.25	0.02	0.01	0.08
β_x* [mm]	1500	500	1000	200
β_y* [mm]	50	1	1	2
Hourglass factor	0.98	0.75	0.65	0.81
SR power/beam [MW]	11	50	50	20
Bunch length [mm]	16	1.7	2.5	3.2
Momentum acceptance [%]	1.25	2.5	2.5	3.0
Beam-beam parameter / IP	0.07	0.1	0.1	0.1
Luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	0.0125	4.8	1.3	1.8

* Assumes 4 IPs   ** Assumes 1 or 2 IPs

e^+e^- Circular Colliders

Status

- TLEP Design Study has been launched
- Not aware of any other significant effort underway

R&D

- Focus on detailed technical assessments
- Challenges, but no obvious showstoppers

Time

- TLEP: Conceptual Design Report by 2015
- TLEP: Technical Design Report by 2018
- TLEP: Aiming for construction readiness in 2020's

Technical Statement

Linear Colliders

- Luminosity

$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y}\mathcal{H}_D$$

$$\mathcal{L} = \frac{P_b}{E_b}\left(\frac{N}{4\pi\sigma_x\sigma_y}\right)\mathcal{H}_D$$

- The strong fields at the interaction point result in
  - A luminosity enhancement characterized by the disruption parameter $\mathcal{H}_D$
  - Beamstrahlung emission gives rise to energy spread and backgrounds at the interaction point

Linear Collider Options

- A range of options have been explored
  - ILC: Based on SRF technology
    Most mature concept for E_{CM}<1 TeV

Yield '10 ~ '12:
> 90% @ 25 MV/m
~ 80% @ 28 MV/m
~ 70% @ 35 MV/m

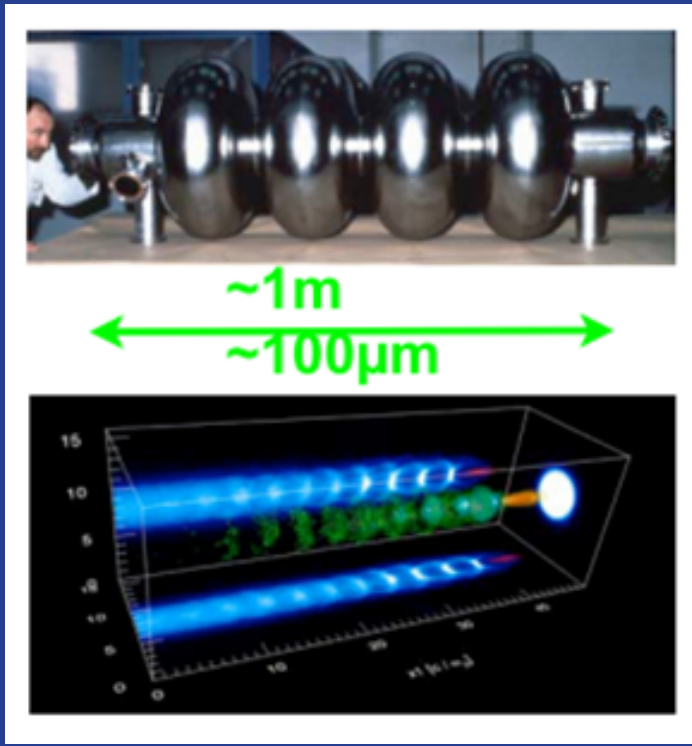
  - CLIC: Based on drive-beam and NCRF technology
    RF Gradients: 100 MV/m
    Could be applied for E_{CM}<1 TeV, but designs up to 3 TeV are documented

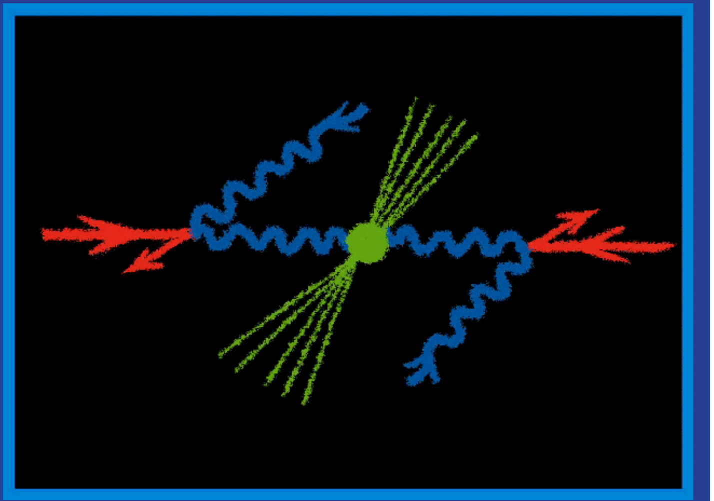
Linear Collider Options

- Options (cont'd)
  - Wakefield Accelerators:
    Potential for very high energies
    Possibly could be used for LC afterburner
    Significant R&D remains
  - γ−γ: High power laser beams
    Compton backscattered from e^- or e^+ beams

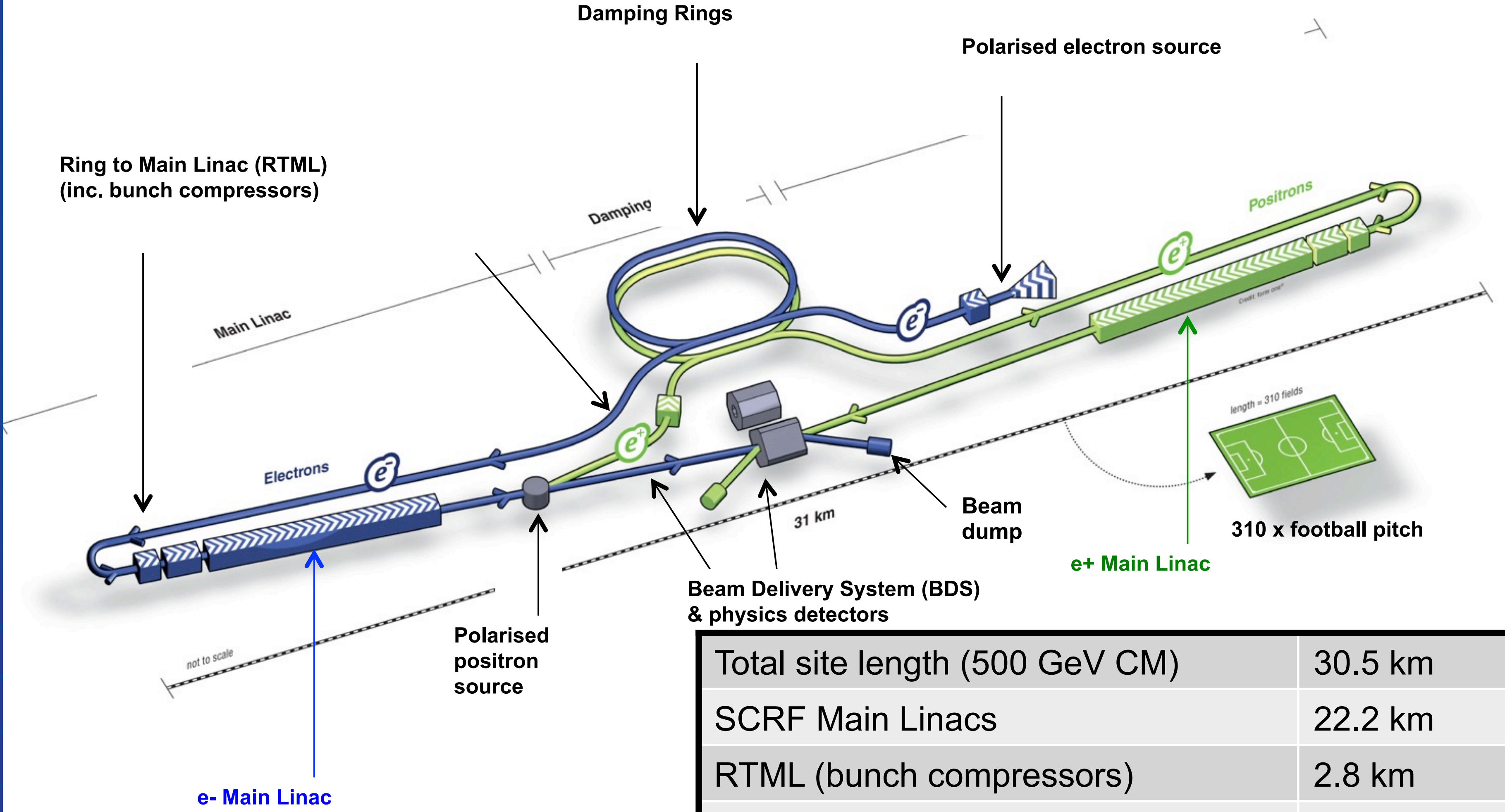
    $\gamma\gamma \Rightarrow H$ cross section ~200fb

    Concept could be applied at an ILC or CLIC





ILC in a Nutshell



Total site length (500 GeV CM)	30.5 km
SCRF Main Linacs	22.2 km
RTML (bunch compressors)	2.8 km
Positron source	1.1 km
BDS / IR	4.5 km
Damping Rings (circumference)	3.2 km

not to scale

ILC Scheme | © www.form-one.de

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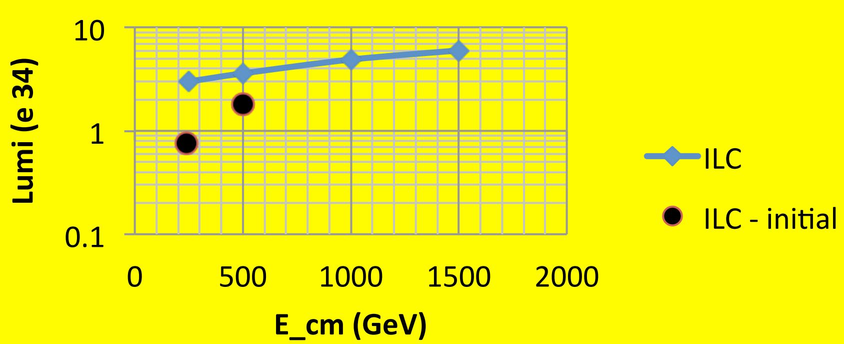
Luminosity

1 TeV 150% *2.4* 263 14.6	**1 TeV Baseline** 166% *4.9* 298 27.3		**1000**	
Baseline 100% *1.8* 163 10.5	**High L** 106% *3.6* 204 21.0		**500**	
LHF 69% *0.75* 129 9.4	**LHF high L** 74% *1.5* 161 11.8	**LHF High L/High P** 106% *3* 204 21	**250**	**E_cm (GeV) -->**
1312	**2625 / (2450 4Hz)**	**2625 10 Hz**		

Number of bunches and repetition rate ->

A factor of 2.5 in L/P_{wall}

Luminosity vs Energy



Legend	
Title	
Rel Cost	***L (e34)***
P_AC	**P_2**
(MW)	**beam**

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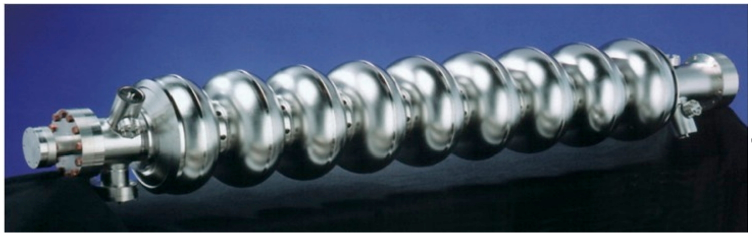
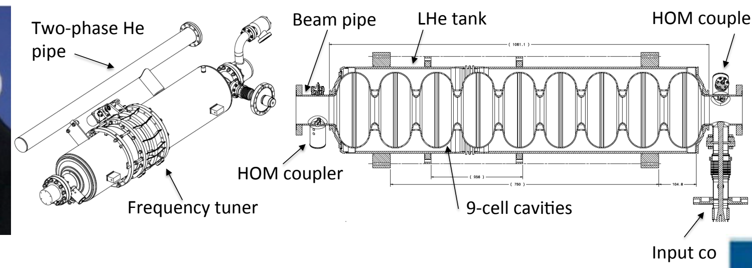
ILC SCRF Technology





1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	436 *

* site dependent

Approximately 20 years of R&D worldwide
→ Mature technology

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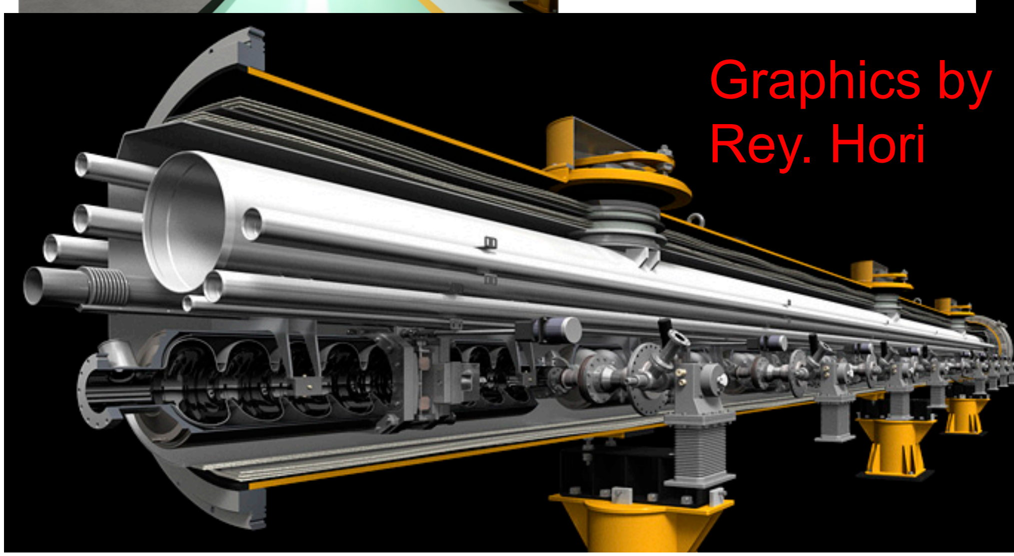
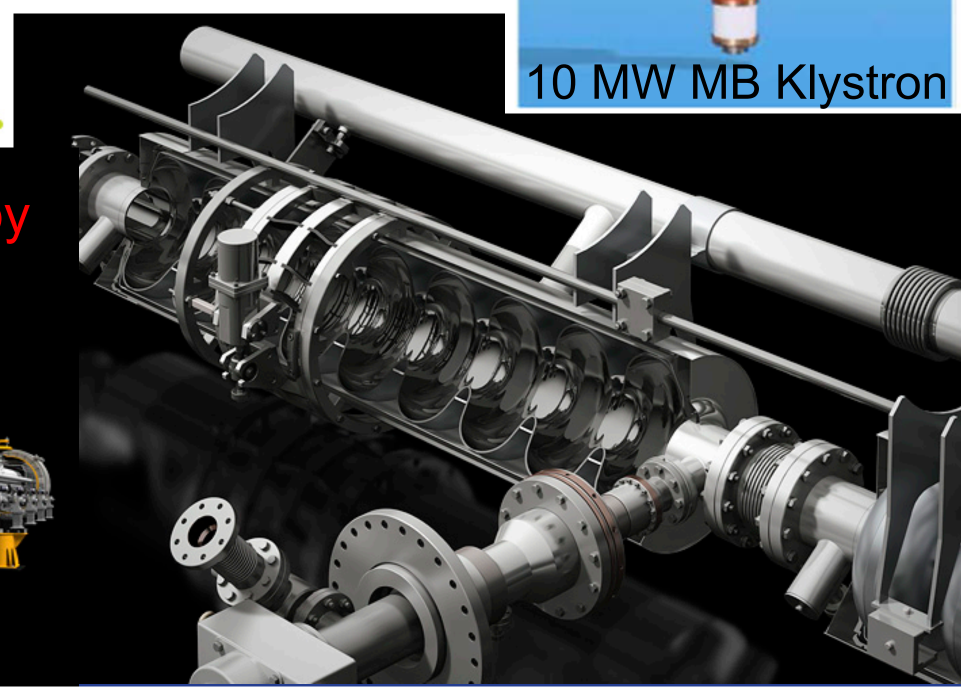
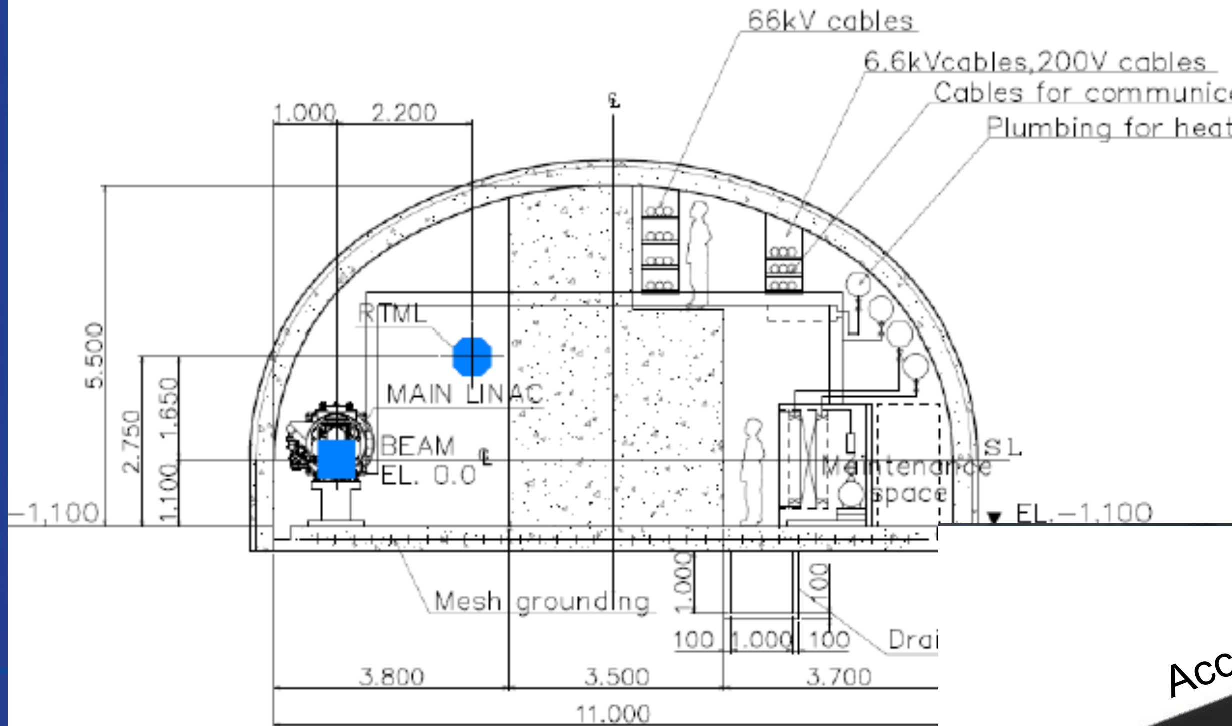




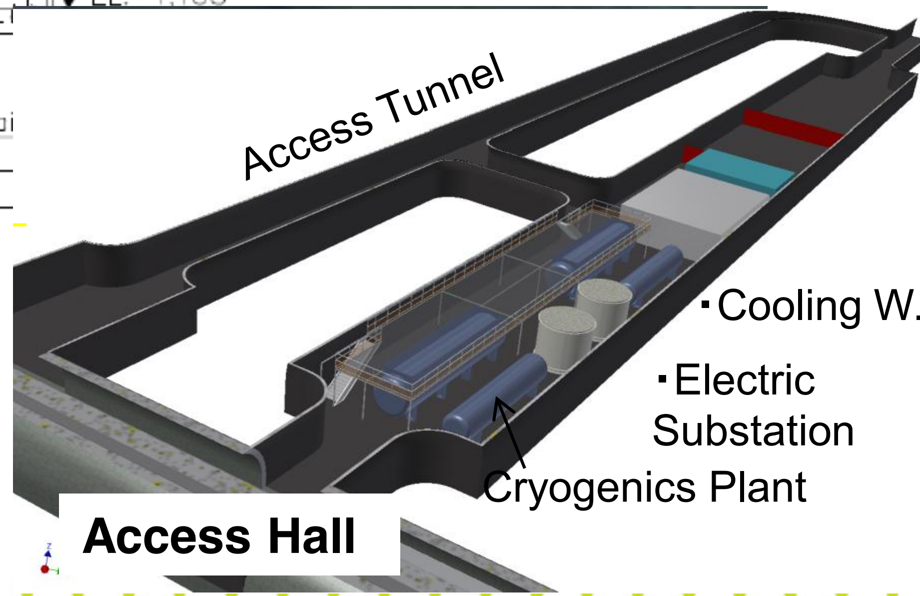
Building ILC in Japanese Mountains:



Reduced surface presence.

Horizontal access

Most infrastructure underground.



“Mountainous” Topography site-dependent design

“Kamaboko” tunnel

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Japanese Siting

Candidate site (1 of 2) in northeastern Japan

Tohoku 'Mountain Region'

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(Photo taken100 km north of Sendai.)

The ILC alignment would be 50 to 400 meters below these hills.

ILC Parameters

Centre-of-mass energy	E_{cm}	**GeV**	**250**	**350**	**500**		**1000**
Beam energy	E_{beam}	GeV	125	175	250		500
Estimated AC power	P_{AC}	MW	128	142	162		300
Collision rate	f_{rep}	Hz	5	5	5		4
Electron linac rate	f_{linac}	Hz	10	5	5		4
Number of bunches	n_b		1312	1312	1312		2450
Bunch separation	Dt_b	ns	554	554	554		366
Pulse current	I_{beam}	mA	5.8	5.8	5.79		7.6
RMS bunch length	σ_z	mm	0.3	0.3	0.3		0.250
Electron polarisation	P_-	%	80	80	80		80
Positron polarisation	P_+	%	30	30	30		20
Luminosity (inc. waist shift)	L	$\times 10^{34}$ $cm^{-2}s^{-1}$	**0.75**	**1.0**	**1.8**		**3.6**
Fraction of luminosity in top 1%	$L_{0.01}/L$		87.1%	77.4%	58.3%		59.2%

The ILC

Status

- Technical Design Report now complete
- Decision point on moving forward has been reached

R&D

- Most significant R&D issues addressed during ILC Technical Design Phase [SRF cavity R&D, including industrialization; FLASH beam tests; damping ring studies, CESRTA; damping ring and beam delivery system studies at KEK-ATF]
- Some technical challenges remain (eg, complete ATF2 program), but no obvious showstoppers

Time

- Team ready to move forward with detailed engineering and site-specific design
- Timescale contingent on decision process and international support

CLIC layout at 500 GeV

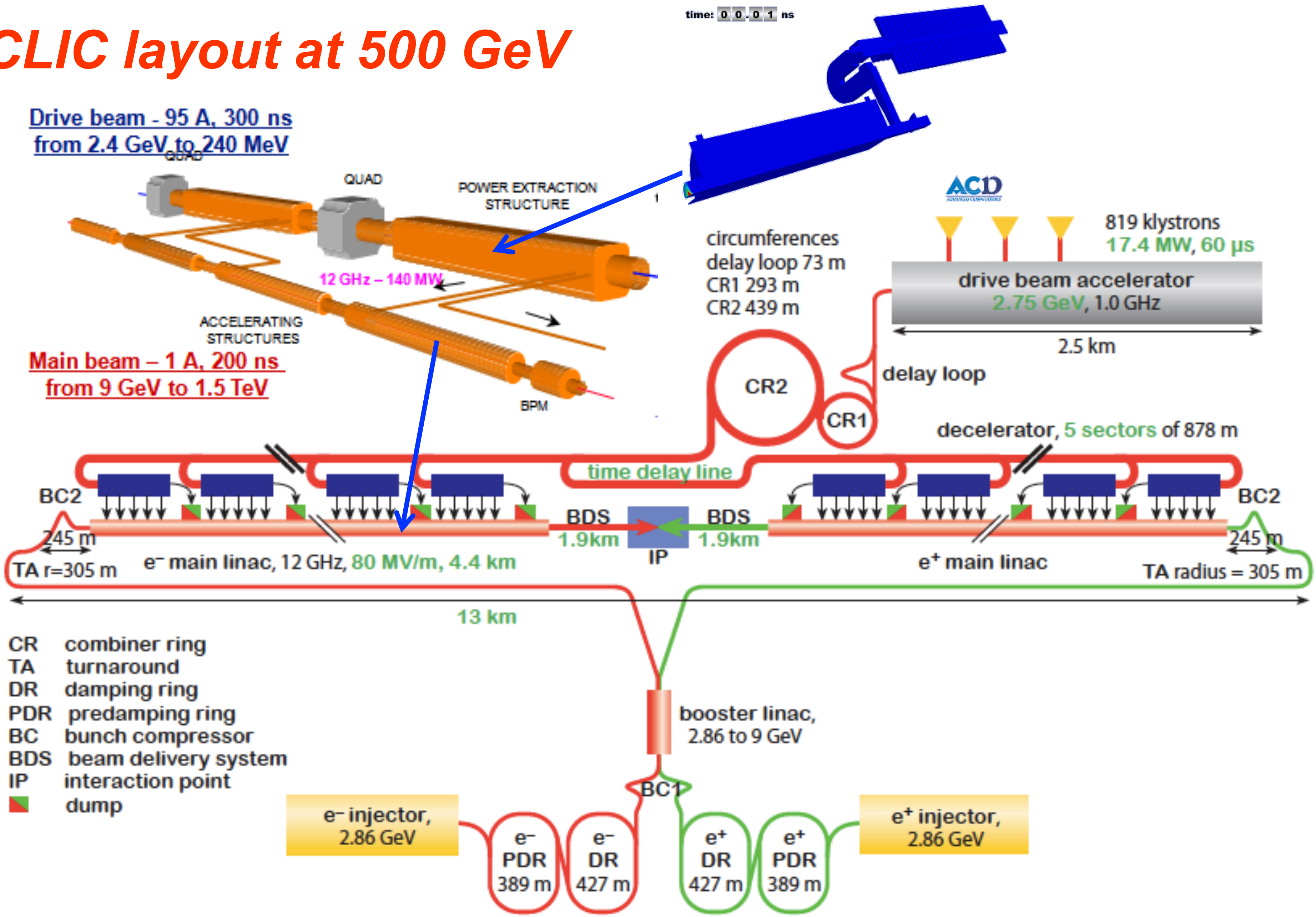


Fig. 3.2: Overview of the CLIC layout at $\sqrt{s} = 500$ GeV.

Potential Staged CLIC Parameters

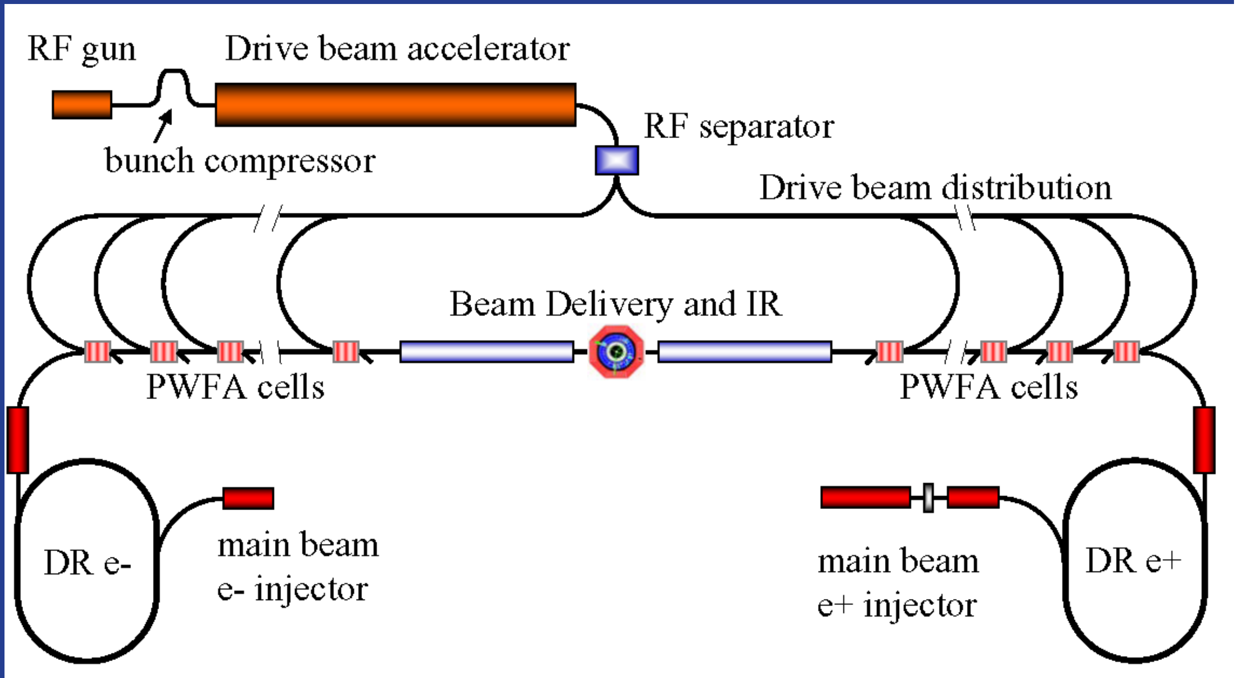
parameter	symbol			
centre of mass energy	E_{cm} [GeV]	500	1400	3000
luminosity	$\mathcal{L}$ [10^{34} cm^{-2}s^{-1}]	2.3	3.2	5.9
luminosity in peak	$\mathcal{L}_{0.01}$ [10^{34} cm^{-2}s^{-1}]	1.4	1.3	2
gradient	G [MV/m]	80	80/100	100
site length	[km]	13	28	48.3
charge per bunch	N [10^9]	6.8	3.7	3.7
bunch length	σ_z [μm]	72	44	44
IP beam size	σ_x/σ_y [nm]	200/2.26	$\approx$ 60/1.5	$\approx$ 40/1
norm. emittance	ϵ_x/ϵ_y [nm]	2400/25	660/20	660/20
bunches per pulse	n_b	354	312	312
distance between bunches	Δ_b [ns]	0.5	0.5	0.5
repetition rate	f_r [Hz]	50	50	50
est. power cons.	P_{wall} [MW]	271	361	582

Linear Colliders with E > 1 TeV

- ILC is ~ 50 km at 1 TeV
  - Possible to consider higher gradient SCRF materials or PWFA boost
- CLIC design is aimed at upgradable design → 0.5-3 TeV
  - Geographic gradient of 4x higher than ILC
- Advanced acceleration options (plasma, dielectric)
  - Plasma acceleration has made great progress however still huge challenges in beam quality and stability
  - Extremely low charge dielectric-laser accelerators may provide only reasonable parameters in multi-TeV regime
  - None of AARD options are close to being ready
- Some plasma and dielectric options act as transformers taking high power beams → high energy beams
  - Possible to develop upgrade options for ILC-like technology?

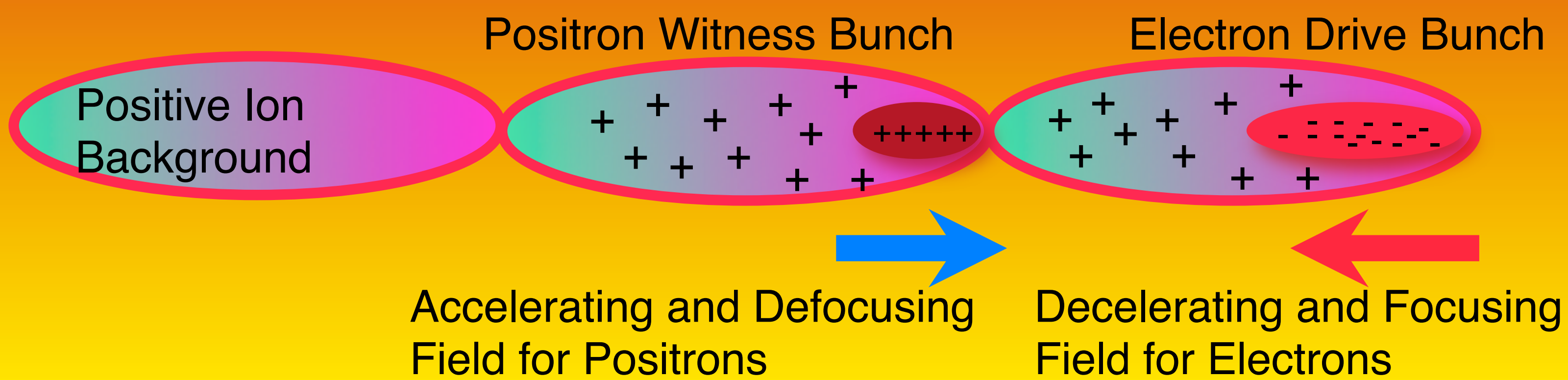
Concept of Beam-Driven Plasma Linac

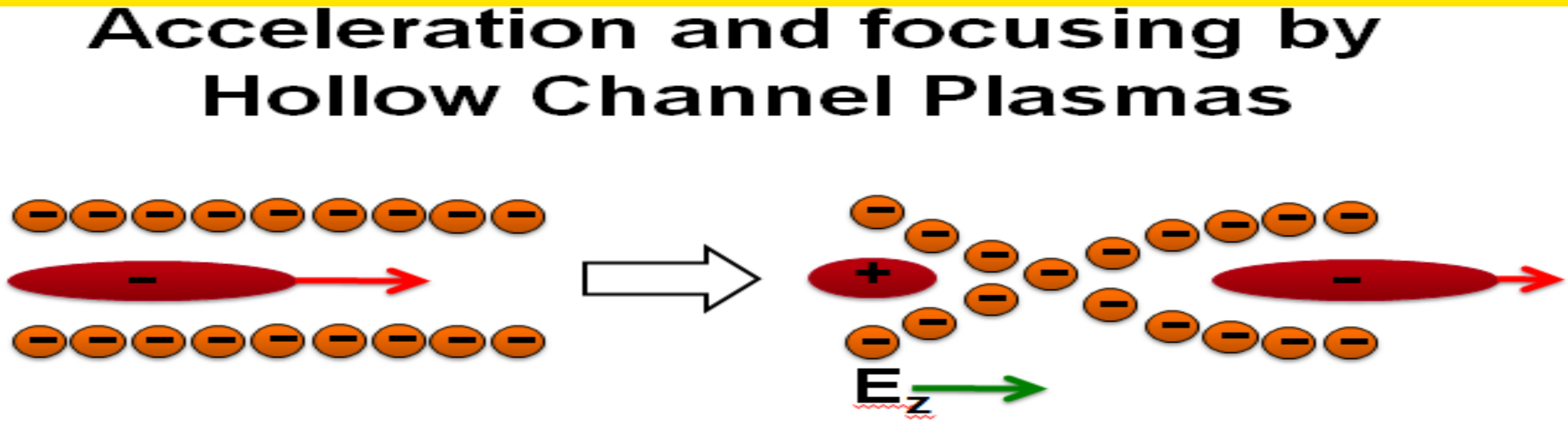
- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes good use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance preservation
    - Positrons
  - Allows study of cost-scales for further optimization of R&D



Challenges for Positron Plasma Wakefield Acceleration

M. Hogan





In a hollow channel plasma, the plasma electrons originate from the same initial radius, and receive a fast kick from the drive beam. They travel toward the beam axis and form a coherent accelerating and focusing wake for positron beam.

Possible Linear Collider Parameters

Case	0.5 TeV ILC	3 TeV CLIC	10 TeV Dielectric Beam Acc.	10 TeV Plasma Accelerator	10 TeV Dielectric Laser Acc.
Energy per beam (TeV)	0.25	1.5	5	5	5
Luminosity (10^{34} cm^{-2}s^{-1})	2	6.4	49	71.4	105
Electrons per bunch ($\times 10^9$)	20	3.7	4	4	0.002
Rep. rate (Hz) / number / train	5 / 1312	50 / 312	50 / 416	17,000 / 1	25,000,000 / 1
Horizontal emittance $\gamma\varepsilon_x$ (nm-rad)	10,000	660	1000	200	0.1
Vertical emittance $\gamma\varepsilon_y$ (nm-rad)	30	20	10	200	0.1
β^* x/y (mm)	11 / 0.2	4 / 0.1	10 / 0.1	0.2	0.4
Horizontal beam size at IP σ^*_x (nm)	474	49	32	2	0.06
Vertical beam size at IP σ^*_y (nm)	3.8	1.0	0.3	2	0.06
Luminosity enhancement factor	1.6	1.9	1.9	1.35	6.05
Bunch length σ_z (μm)	300	50	20	1	335
Beamstrahlung parameter Υ	0.07	6.7	56	8980	0.4
Beamstrahlung photons per electron n_γ	1.7	1.5	1.4	3.67	0.5
Beamstrahlung energy loss δ_E (%)	4.3	33	37	48	4.3
Accelerating gradient (GV/m)	0.031	0.1	0.5	10	0.5
Average beam power (MW)	5.3	13.9	55	54	38
Wall plug power (MW)	200	568	~1200	~1200	~550
One linac length (km)	15.5	23.5	10	1.0	10.5

ILC and CLIC parameters from design reports; 10 TeV DBA scaled from Wei Gai communication; 10 TeV DLA and Plasma Accelerator from 2010 ICUIL/ICFA Workshop

CLIC and Wakefield LCs

Status

- CLIC Conceptual Design Report complete
- Wakefield Accelerator Concepts – Feasibility being assessed

R&D

- CLIC: Focus on technology and advanced systems R&D
- Wakefield Accelerators:
  - Ability to accelerate positrons
  - Demonstration of multi-stage acceleration
  - Understanding the extrapolation of all parameters to the regimes required for HEP accelerator use (emittance preservation, achievable energy spread, beam loading, repetition rate)

Time

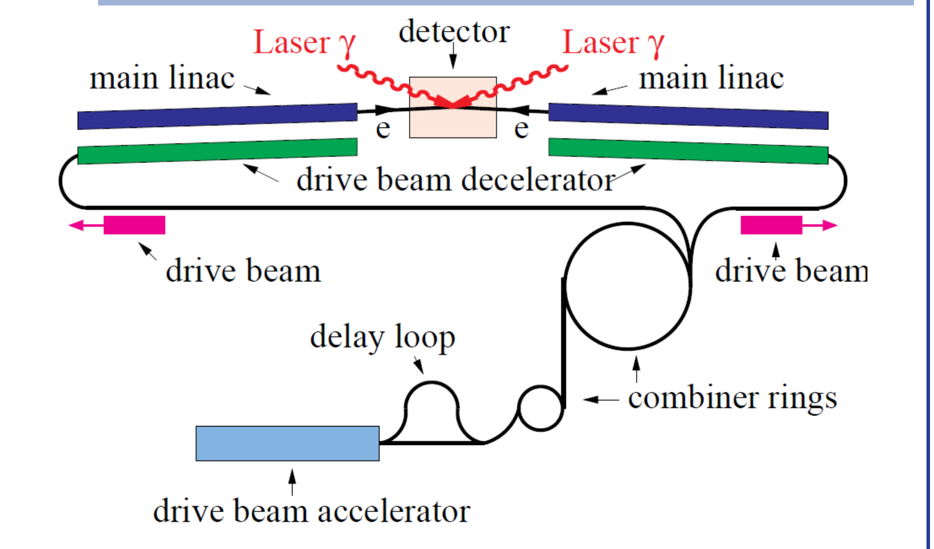
- CLIC: Timescale dependent on finalized technical design and physics needs
- Wakefield LCs:
  - Expect non-HEP applications on the ~decade timescale
  - Collider R&D phase to fully assess feasibility is likely decades scale
  - First application might be an ILC “afterburner”

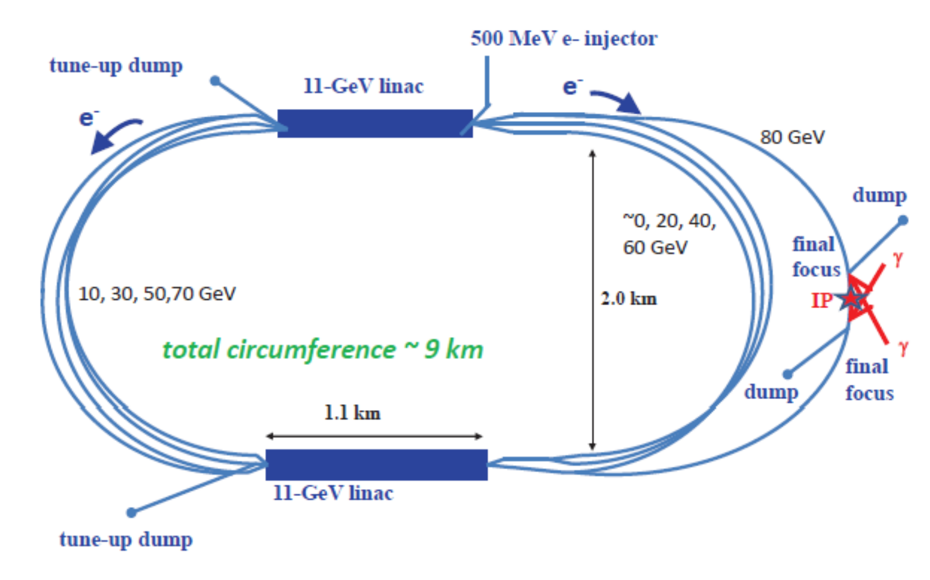
γ–γ Collider Concepts

- γ–γ Higgs Factory (E_{CM}~160 GeV, photons carry ~80% of CM E) might represent a `low cost' option to demonstrate the technology
- Relative to LC: No positrons, damping rings, bunch compressors, …
- Laser parameters are challenging; requires optical cavity schemes

	SAPPHiRE
Beam Energy	80 GeV
Power Consumption	100 MW
Polarization	80%
Ave Beam Current	0.32 mA
E-e- geometric luminosity	2.2x10^34
Laser wavelength	351 nm
Repetition rate	200 kHz
Laser pulse energy	~5 J

CLICHÉ: CLIC Higgs Experiment





$\gamma-\gamma$ Colliders

Status

- Principal technical challenge is laser system
- Question: Would the community be interested in a standalone facility versus eventual companion capability with an e^+e^- LC? Can this provide the required physics?

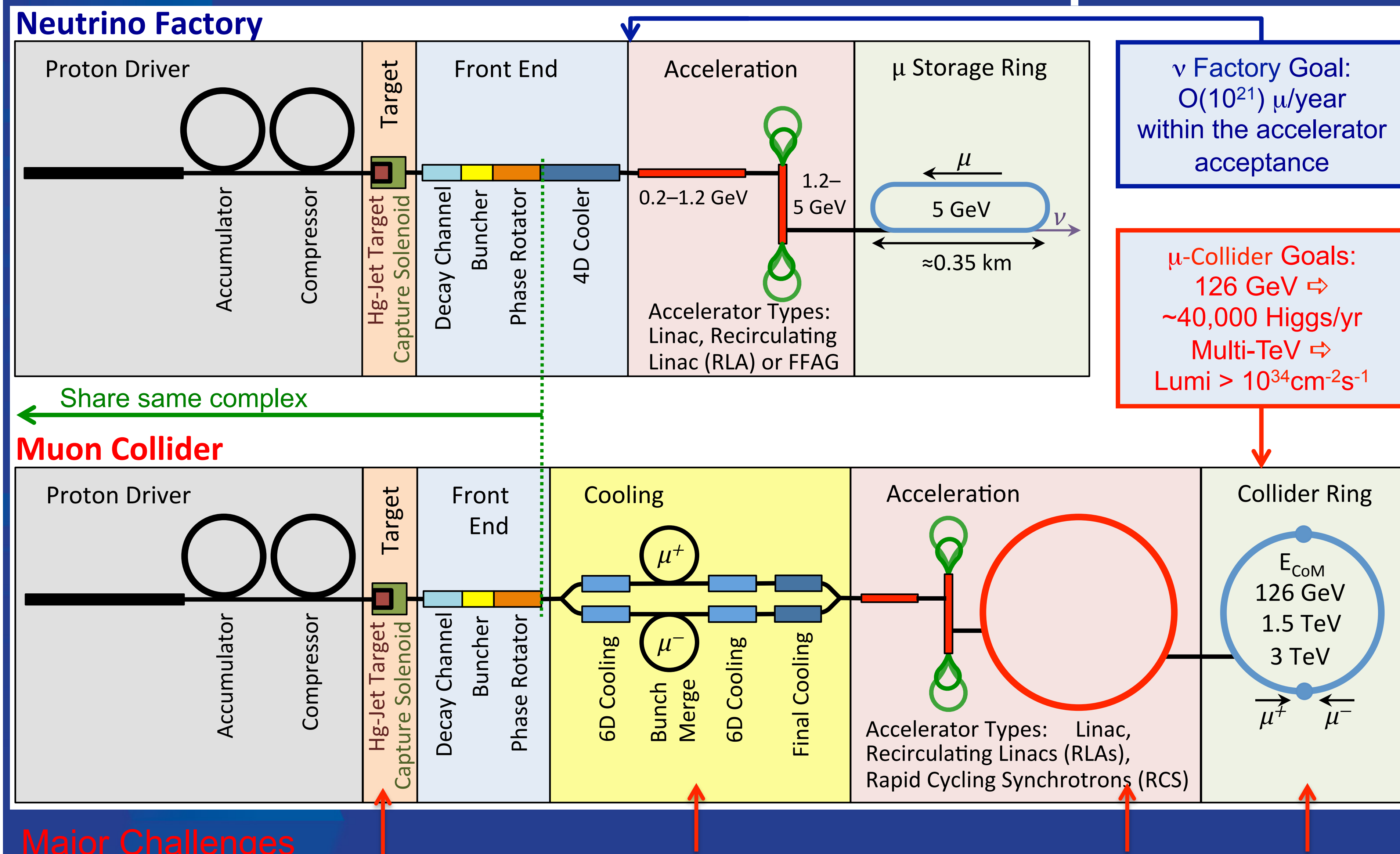
R&D

- Validate feasibility of required laser – significant recent progress
- Would need to establish a full Technical Design

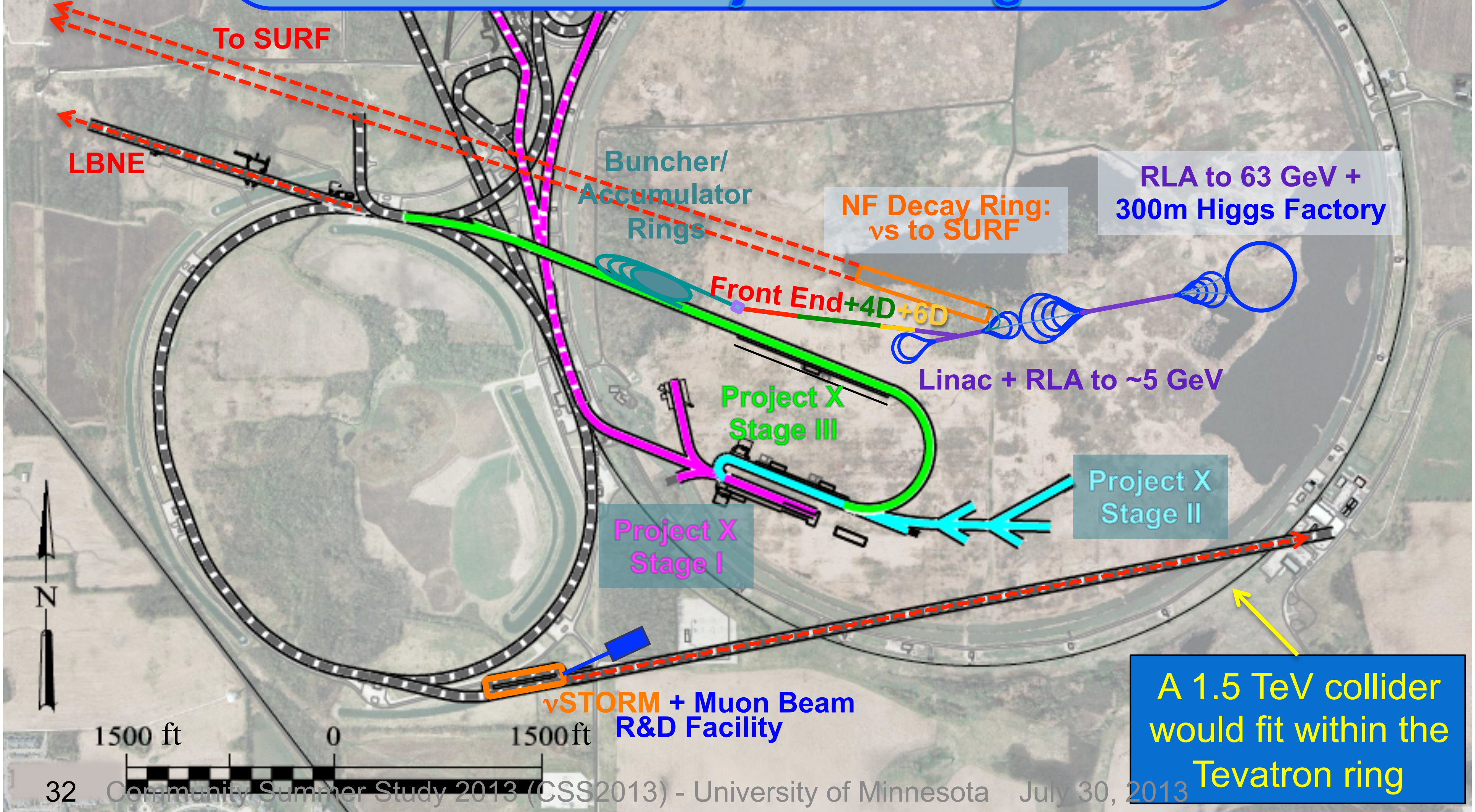
Time

- In principle, a decision point could be reached in a few years

Muon Accelerator Concepts



A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II



MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Colliders

Range of Top Params:
$\delta E/E \sim 0.01 - 0.1\%$
$L_{avg} \sim 0.7 - 6 \times 10^{33}$

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design: ≤ 10 TeV

Muon Collider Baseline Parameters

Parameter	**Units**	Higgs Factory: Startup Operation	Higgs Factory: Production Operation	Multi-TeV Baselines	Multi-TeV Baselines
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4#	4	4	4

Could begin operation with Project X Stage 2 beam

Success of advanced cooling concepts ⇨ several × 10^{32}

Muon Colliders

Status

- MAP Feasibility Assessment underway

R&D

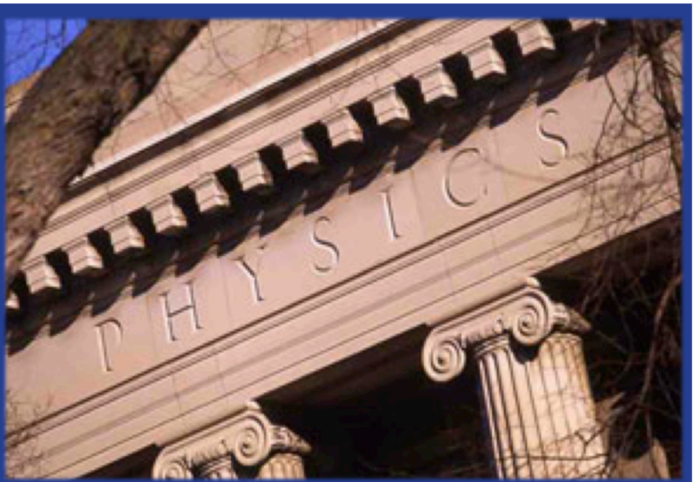
- Establishing Initial Baseline Design
- Technology R&D: Cooling channel hardware, RF in B-fields, high field magnets (synergistic with HE-LHC needs)
- Staging Study: Physics + R&D + Demos required for next stage
- Muon Ionization Cooling Experiment

Time

- Feasibility Assessment by end of decade
- Completion of MICE by end of decade
- NuMAX (initial long baseline NF): Informed Decision by ~2020
- Collider Program: Informed Decision by mid-2020s

Long-Term Perspective

Conclusions

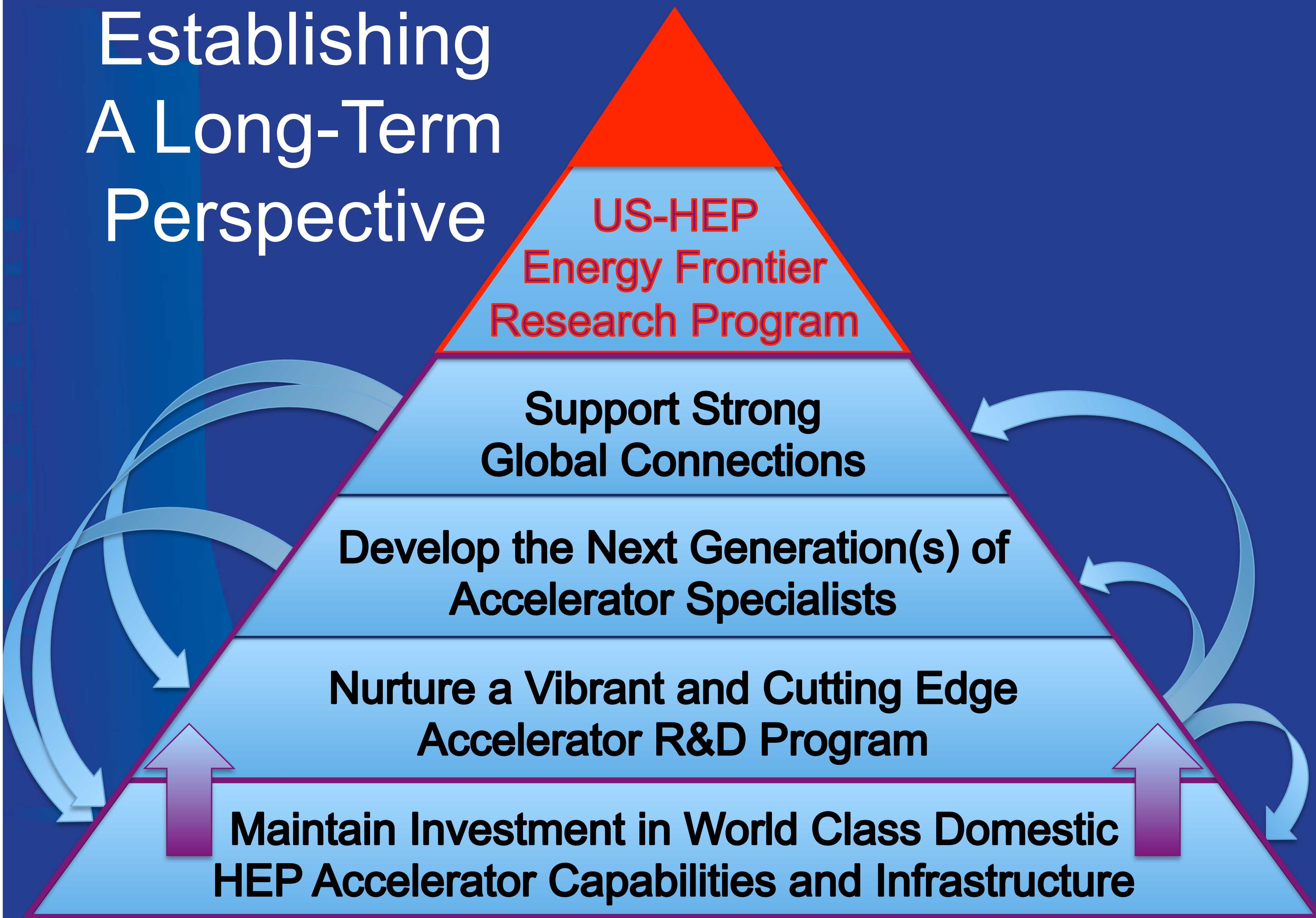


CLOSING REMARKS

Some Connections…

- A theme that has arisen in the capabilities discussions has been that of upgrade paths
  - Note that a number of “constrained” options didn’t even get mention in this presentation
- There are many special synergies that also come into play:
  - TLEP and a ~100 TeV hadron collider
  - Muon Collider and the Neutrino Program
  - Technology linkages (eg, MAP and HE LHC magnet development)
  - γ–γ as a companion capability to an LC
  - A wakefield accelerator upgrade to a conventional LC
  - And this is not an exhaustive list…

Establishing A Long-Term Perspective



What do you get for a Billion Dollars?

NSLS-II: $0.9B, 0.8 km storage ring

SNS: $1.4B, 1 GeV Linac, Ring, high-power target, 1km

S. Henderson
HF2012

Jim Siegrist's "Boundary Conditions"

- **Note that a 'brute force' approach that seeks to spend vast sums in order to build some facility/physics capability simply will not work in today's fiscal environment. This has been empirically demonstrated.**
  - Most recently, via our discussions on LBNE, we have confirmed that single domestic project expenditures must be somewhat smaller than $1B per stage.
- **CSS2013 participants are encouraged to think about whatever physics you think is most relevant and important to progress in HEP, but the effort you put in should be tempered with a realistic assessment of funding possibilities.**
  - Many ideas can be staged to provide new physics capability at each step, but some cannot.
- **Stringing together projects that build upon previous investments either scientifically or through recycling of infrastructure is generally well received.**

Jim Siegrist, CPM2012

https://indico.fnal.gov/getFile.py/access?contribId=4&sessionId=2&resId=3&materialId=slides&confId=5841

- It's imperative to make the case for the physics we need,
- But we must also develop a coherent plan that is realistic if we want to preserve the health and vitality of the U.S. HEP program
- The challenges for <u>**all**</u> of the options presented here go beyond the technical

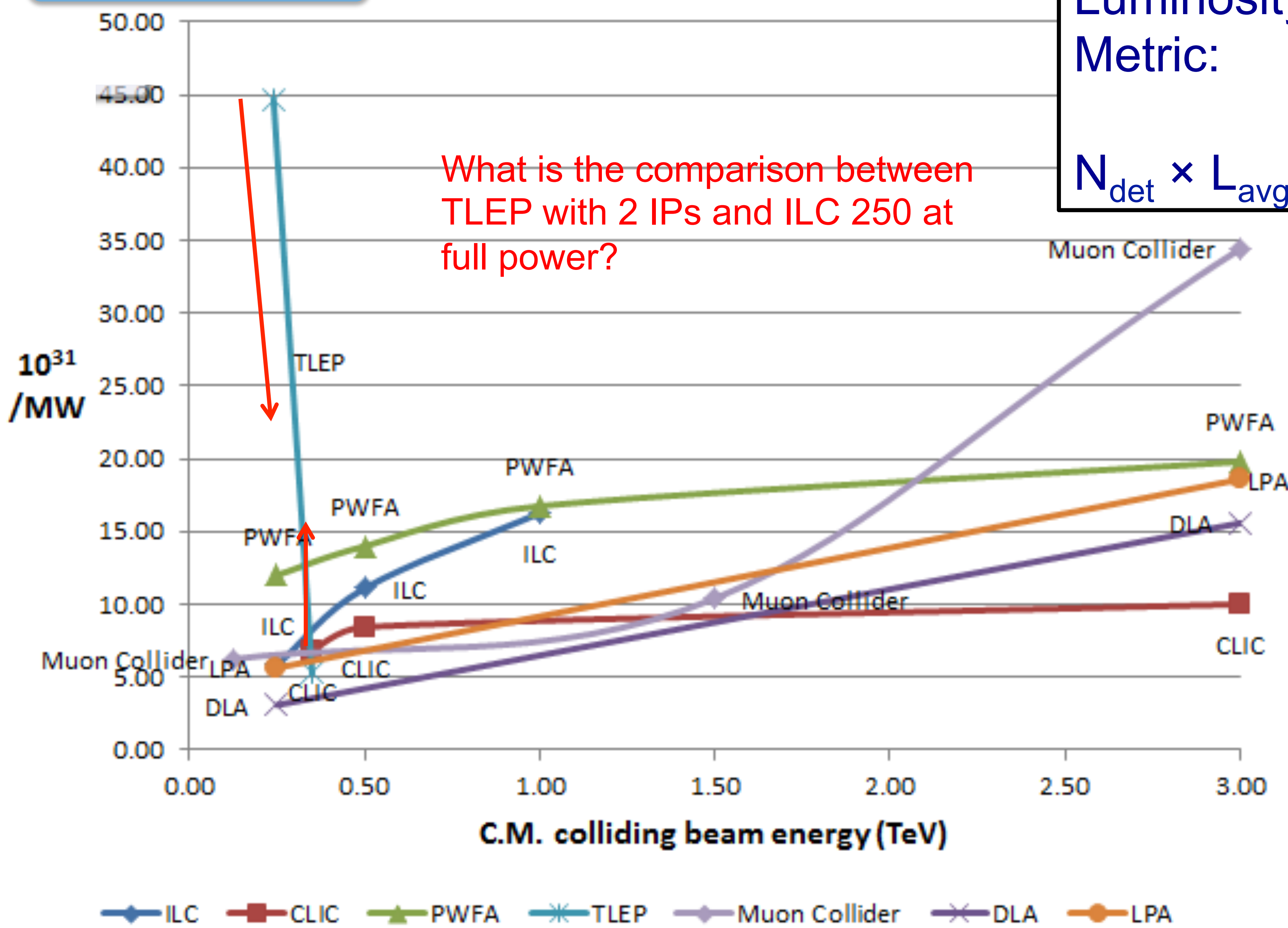
Conclusions I

- The LHC program for the next 20 years is well-defined
  - Questions arise as to what comes next
    - For example: Is an investment in a facility such as TLEP desirable on the 10 year timescale because it can lead to a VHE-LHC/VLHC capability in ~30 years?
- There is little question that the ILC design is, at present, the most complete and well-studied design for a machine targeted at the Higgs
  - But, what will we do if the next round of LHC data finally shows something at > 1 TeV?
  - On the relevant timescale (assuming advances in the R&D program), we may want to consider comparisons such as the plot on the next page…

J-P. Delahaye

Luminosity Metric:

$N_{det} \times L_{avg} / P_{tot}$



Conclusions II

- The necessity of US engagement in the ongoing LHC program is clear
- As is maintaining global connections if the next collider facility is off-shore
- At the same time we cannot ignore other elements of the US HEP program
  - Investing in our domestic facilities which support non-collider portions of HEP
  - Maintaining a robust R&D program which benefits both our global connections and can open the door to additional world class capabilities in the US
  - And continue to train the experts to support the next generation of facilities